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RESEARCH MEMORANDUM

AIRPLANE MEASUREMENTS OF ATMOSPHERIC TURBULENCE FOR
ALTITUDES BETWEEN 20,000 AND 55,000 FEET OVER
THE WESTERN PART OF THE UNITED STATES

By Thomas L. Coleman and Emilie C. Coe

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**NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS**

WASHINGTON

August 23, 1957

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SUMMARY

A sample of data on atmospheric turbulence has been obtained from NACA VGH records taken on Lockheed U-2 airplanes during research flights covering approximately 40,000 miles for altitudes between 20,000 and 55,000 feet over the western part of the United States. An analysis of these data has indicated that the intensity, amount, and extent of atmospheric turbulence is in good agreement with earlier measurements obtained over England and Western Europe. In comparison with past estimates of average turbulence conditions over the United States, the results of this investigation, in general, indicate somewhat lower gust frequencies and lower gust intensities.

INTRODUCTION

During the early part of 1956, the National Advisory Committee for Aeronautics, in cooperation with the Air Weather Service of the United States Air Force, initiated a high-altitude flight research program aimed at providing detailed meteorological information for various geographic areas of the world (ref. 1). The NACA participation in the program has been aimed primarily at obtaining information on the amount and intensity of atmospheric turbulence at high altitudes for use in airplane and missile response studies; whereas, the Air Weather Service has aimed at collecting data on humidity, pressure variations, and winds for associated operational and meteorological analysis.

The initial flight operations included in the program were undertaken concurrently over the western part of the United States and over England and Western Europe in the spring of 1956 and covered altitudes up to 55,000 feet. An analysis of the gust measurements obtained from the operations over England and Western Europe has been reported in

reference 1. The results for the intensity and percent of rough air from the European operations were found to be in overall agreement with the estimates given in reference 2 for turbulence at high altitudes over the United States, although some differences in the intensity of turbulence for the two areas were indicated.

A sample of data on atmospheric turbulence covering approximately 40,000 flight miles for altitudes between 20,000 and 55,000 feet has been obtained from the operations over the western part of the United States. The present paper presents the results obtained for the frequency and intensity of the turbulence encountered in these operations and compares these results with those given in references 1 and 2.

INSTRUMENTATION AND SCOPE OF DATA

The flight measurements were obtained during flights of several Lockheed U-2 airplanes. The Lockheed U-2 is a subsonic, straight-wing, single-engine, jet airplane originally designed for use as a high-altitude test vehicle. A photograph of the test airplane is shown in figure 1.

The measurements pertinent to this report consisted of time-history records of airspeed, acceleration, and pressure altitude taken with NACA VGH recorders (ref. 3). The time histories were recorded on photographic paper moving at 4 inches per minute.

Inasmuch as the major interest of the present program is in meteorological conditions at high altitudes, the flight plans for the operations were selected to provide maximum sampling time and coverage above 50,000 feet. In general, the flight plans consisted of climbing to an altitude of approximately 50,000 feet in the vicinity of the operations base (Watertown Strip, Nevada), cruising initially at about 50,000 feet with the altitude gradually increasing to about 55,000 feet as the fuel load decreased, and then descending to the operations base. As a consequence of this flight procedure, the gust measurements below 50,000 feet were obtained only during the climb and descent phases of the flight and the measurements above 50,000 feet were taken primarily during cruising flight. The data below 50,000 feet essentially represent soundings of the atmosphere and thus reflect the turbulence conditions which exist in the general region of Watertown Strip, Nevada. The cruise portions of the flights between 50,000 and 55,000 feet, in general, covered the Rocky Mountain and the Pacific Coast regions of the United States.

Records were obtained from 24 flights during operations from Watertown Strip, Nevada, between May 1956 and March 1957 with about one-half of these flights being made during the three-month winter season from December 1956

to February 1957. The flight schedules were based primarily on airplane and instrumentation availability, and no attempt was made to schedule flights to sample turbulence for specific meteorological conditions. Except for occasional penetrations of stable cloud formations while climbing or descending, the flight miles flown during the present operations were in clear air. The data above 50,000 feet, therefore, are felt to be fairly representative of clear-air turbulence conditions over the western part of the United States.

The scope of the data in terms of miles flown within different altitude intervals is listed at the bottom of table I. As shown in the table, about 37,000 flight miles or approximately 90 percent of the total flight miles were flown between 40,000 feet and 55,000 feet, and only a relatively small number of flight miles were in each of the two lower altitude intervals.

EVALUATION OF DATA

The NACA VGH records were evaluated to obtain the derived gust velocities, the percent of rough air at various altitudes, and the length (along the flight path) of the turbulent areas encountered. The evaluation procedures are similar to the procedures used in references 1 and 2 and are given briefly in the following paragraphs.

The vertical gust velocities were derived from simultaneous readings of acceleration, airspeed, and altitude through the use of the gust equation which is given in reference 4 as

$$U_{de} = \frac{2a_n W}{m_p \frac{K}{o} \frac{V}{g} \frac{S}{e}}$$

where

U_{de}	derived gust velocity, fps
a_n	peak normal acceleration, g units
W	airplane weight, lb
S	wing area, sq ft
K_g	gust factor
V_e	equivalent airspeed, fps

m wing lift-curve slope per radian
 ρ_0 air density at sea level, slugs/cu ft

In evaluating the records, the accelerations were read to a threshold sufficiently low to yield complete frequency counts of all gust velocities greater than 2 feet per second. Values of airspeed and pressure altitude were obtained from the records for each acceleration evaluated. The weight loss during flight was accounted for in determining the values of wing loading W/S for use in the equation. Appropriate values of the gust factor K_g were computed for each part of the record where rough air was encountered. The values of the lift-curve slope m used in deriving the gust velocities were based on data obtained from the airplane manufacturer.

The gust-velocity values presented herein may be open to some question because of effects of airplane flexibility and stability on the accelerations from which the gust velocities were computed. The magnitude of these effects is not known at present, and additional work is required before their influence on the gust-velocity values can be assessed.

For the purpose of determining the length of the turbulent areas, the airplane was considered to be in rough air whenever the accelerometer trace was continuously disturbed and contained accelerations corresponding to gust velocities greater than 2 feet per second. This threshold value of 2 feet per second corresponds to that used in previous gust studies, such as references 1 and 2. The length of each turbulent area was found simply by multiplying the true airspeed by the time spent in the rough air. The summation of the lengths of the individual areas of rough air was divided by the total flight distance for given altitude intervals in order to obtain the percent of rough air for that altitude interval.

RESULTS AND DISCUSSION

Overall Gust Distributions

The gust velocities derived from the acceleration and airspeed data are presented as frequency distributions in table I for several altitude intervals between 20,000 and 55,000 feet. Inspection of the table shows that the maximum gust velocities encountered in the present operations were approximately 12 feet per second and were experienced in altitude intervals from 20,000 to 30,000 feet and from 50,000 to 55,000 feet. Only 19 gusts above 2 feet per second were encountered in approximately 7,000 miles of flight in the altitude interval between 40,000 and 50,000 feet and, consequently, the distribution of gust velocities for

this altitude interval is not well defined. As noted previously, the data below 50,000 feet were obtained during the climb and descent portion of the flights and may be biased by turbulent conditions peculiar to the general region of Watertown Strip, Nevada.

The gust-velocity data from table I are shown in figure 2 as cumulative frequency distributions per mile of flight for each altitude interval. These cumulative frequency distributions give the average number of gusts per mile of flight which exceeded given values of gust velocity. Examination of figure 2 shows that large variations exist in the frequency with which given gust velocities were encountered in the various altitude intervals and that, in general, the gust frequency decreased with increasing altitude.

Figure 3 compares the present results for the gust frequency at the different altitudes with the results for corresponding altitudes from references 1 and 2. The results from reference 2 are based on the basic distribution of nonthunderstorm turbulence and the variation of gust intensity with altitude. It should be noted that the present results and those from reference 1 are for specific geographical regions, whereas the results from reference 2 are estimates of average turbulence conditions over the United States.

Inspection of figure 3 shows that the present results are in good agreement with the results from reference 1 for operations over Western Europe, except for the altitude interval of 40,000 to 50,000 feet. Both sets of data from the present investigation and reference 1 indicate lower gust frequencies for each altitude interval than those given by the estimates based on reference 2. Thus, it appears that estimates of gust frequencies for clear-air turbulence based on reference 2 may be somewhat high in comparison with operations over the western part of the United States and Western Europe.

Intensity of Turbulence

The overall gust distributions discussed in the preceding section may be considered to reflect the combined effects of the intensity of the turbulence and the percent of rough air at the various altitudes. In order to examine the turbulence encountered in more detail, it is helpful to consider separately the gust intensity and the percent of rough air. As a measure of the severity of the turbulence, the cumulative frequency distributions of gust velocity per mile of flight in rough air are plotted in figure 4 for the various altitude intervals. Inspection of figure 4 shows that differences on the order of 20 to 1 exist between the frequency of occurrence of given gust velocities per mile of flight in rough air at the various altitudes. Although the results indicate a lower gust intensity for the highest altitude interval

(50,000 to 55,000 feet) than for the lowest altitude interval (20,000 to 30,000 feet), these results do not exhibit the continuous decrease in gust intensity with increasing altitude shown by previous results (ref. 2).

In order to compare the present results for the intensity of turbulence with previous results, the cumulative frequency distributions of gust velocities per mile of flight in rough air within different altitude intervals are shown in figure 5 together with corresponding results from references 1 and 2. These results indicate that, in general, the intensity of the rough air encountered in this investigation is approximately the same as that reported in reference 1 for operations over Western Europe but is lower than that estimated in reference 2 for average operations over the United States. For the altitude interval of 30,000 to 40,000 feet, in particular, the intensity of the turbulence encountered in both the present investigation and in reference 1 appears to be much lower than is shown by the estimates from reference 2.

Percent of Rough Air

The percent of the flight distance which was in rough air is presented in figure 6 for each 5,000-foot altitude interval. For comparison, similar results from references 1 and 2 (the latter results based on airplane and telemeter data) are also given in the figure. Figure 6 indicates that the percent of rough air from both the present flights and European flights (ref. 1) is in fair agreement with the results of reference 2 at the lowest and highest altitudes, but that the data from the present report and from reference 1 indicate a much higher percent of rough air between 30,000 and 40,000 feet.

It may be noted that the percent of rough air (ref. 2) is based on a fairing of some of the earliest available data on the variation of the percent of rough air with altitude. Although some of these early data indicated a peak in the percent of rough air at altitudes of 30,000 to 40,000 feet, this indication was given little weight in the fairing because of the limited data available at that time. The consistency of the two sets of results from the present report and from reference 1 and reconsideration of the earlier data used in reference 2, however, suggest that a peak does exist between 30,000 and 40,000 feet in the variation of the percent of rough air with altitude. As noted previously, however, the intensity of the turbulence for this altitude interval is relatively low. This increase in the percent of rough air is probably associated with high winds and wind shears which are prevalent at 30,000 to 40,000 feet for the regions covered by the data (refs. 5 and 6).

Size of Turbulent Areas

The distribution of the lengths of the turbulent areas is given in figure 7 as the percent of the total number of areas which was within class intervals of 10 miles. For comparison, the distributions of turbulent areas given in references 1 and 2 are also shown in the figure. Inspection of the results in figure 7 shows that the distribution of turbulent areas from this investigation is in good agreement with the results from references 1 and 2 and that the majority of the turbulent areas were less than 20 miles in length. A breakdown of the present data showed no significant variations between the distributions of the lengths of turbulent areas for altitudes of 20,000 to 50,000 feet and for 50,000 to 55,000 feet. This result is in agreement with the results of references 1 and 2.

CONCLUDING REMARKS

The results of an analysis of a sample of data on atmospheric turbulence obtained from NACA VGH recorders during research flights of Lockheed U-2 airplanes to altitudes of 55,000 feet over the western part of the United States between May 1956 and March 1957 substantiate earlier indications of a decrease in the frequency of occurrence of gusts with increasing altitude. The intensity of the turbulence, the percent of rough air, and the length of the turbulence areas generally were found to be in good agreement with the results given in NACA Research Memorandum L57A11 for operations over England and Western Europe. In comparison with the earlier estimates given in NACA Research Memorandum L53G15a for operations over the United States, however, the present results generally show a lower gust frequency and lower gust intensities. In addition, the present results and those of NACA Research Memorandum L57A11 indicate a higher percent of rough air between 30,000 and 40,000 feet than is given by the estimates in NACA Research Memorandum L53G15a. These results, together with a reconsideration of earlier data, suggest that a peak exists in this altitude range in the percent of rough air with altitude. However the intensity of the turbulence in this altitude range appears to be light.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 17, 1957.

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TABLE I.- FREQUENCY DISTRIBUTIONS OF DERIVED GUST VELOCITY
FOR VARIOUS ALTITUDE INTERVALS

Gust velocity, U_{de} , fps	Frequency distribution of gust velocity for altitudes of -			
	20,000 to 30,000 ft	30,000 to 40,000 ft	40,000 to 50,000 ft	50,000 to 55,000 ft
2 to 3	142	83	18	120
3 to 4	41	13	1	57
4 to 5	16	4		28
5 to 6	8	1		10
6 to 7	6	1		9
7 to 8	1			3
8 to 9	1			1
9 to 10	0			1
10 to 11	1			0
11 to 12	0			1
12 to 13	1			
Total	217	102	19	230
Miles of flight in rough air	114	216	57	366
Total flight miles	1,203	1,430	6,962	30,244

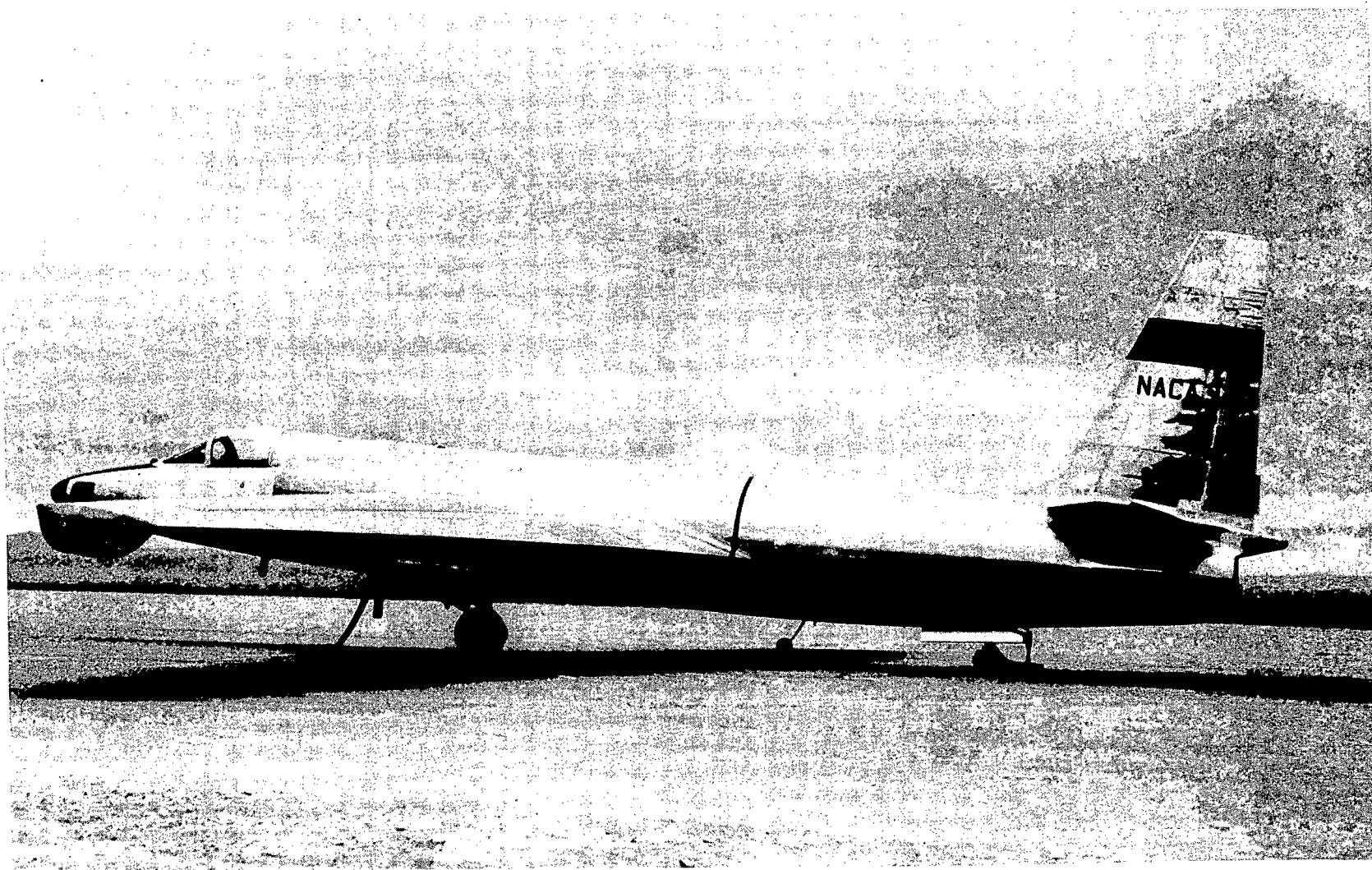


Figure 1.- Photograph of test airplane.

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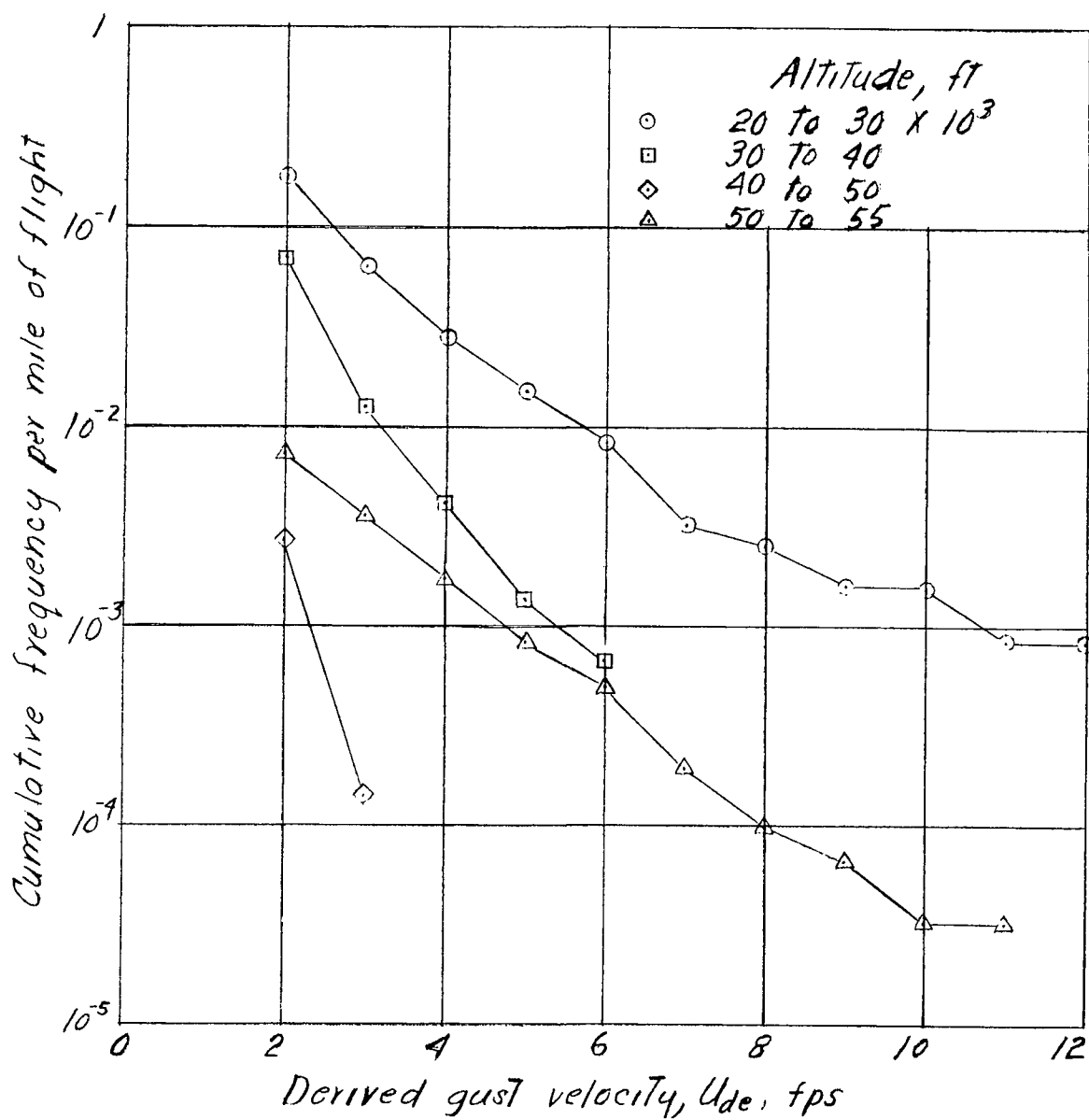
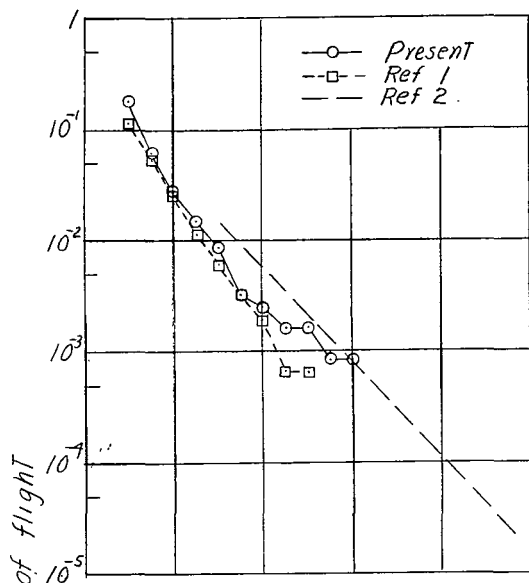
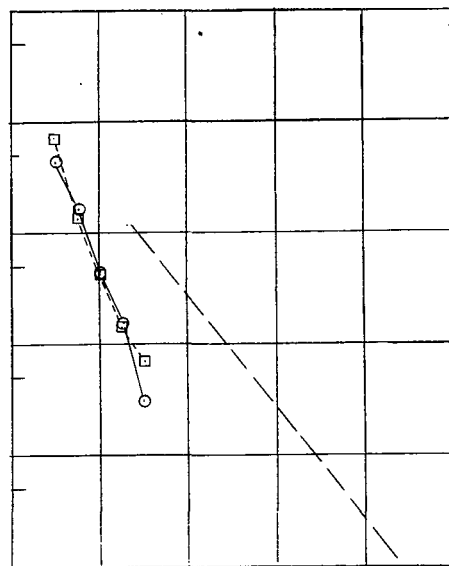


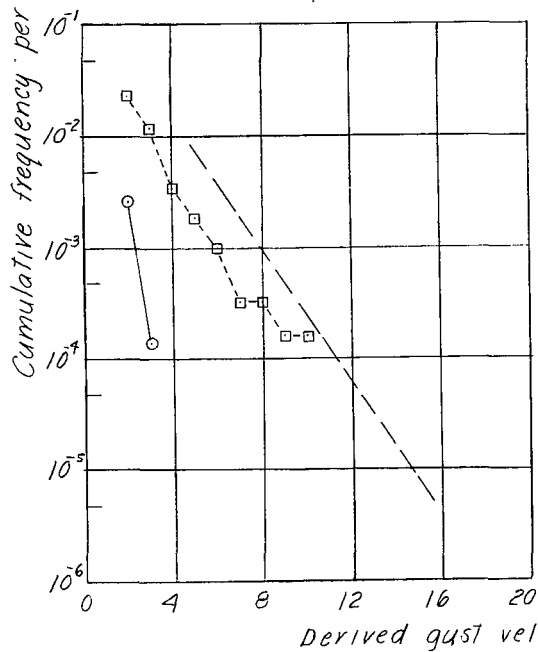
Figure 2.- Variation with altitude of the frequency of exceeding given values of gust velocity per mile of total flight.



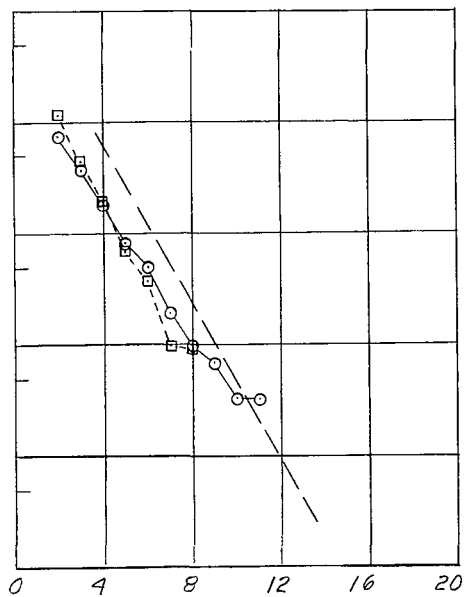
(a) 20,000 to 30,000 feet.



(b) 30,000 to 40,000 feet.



(c) 40,000 to 50,000 feet.



(d) 50,000 to 55,000 feet.

Figure 3.- Comparison at various altitudes of present results for the frequency of exceeding given values of gust velocity per mile of flight with results from references 1 and 2.

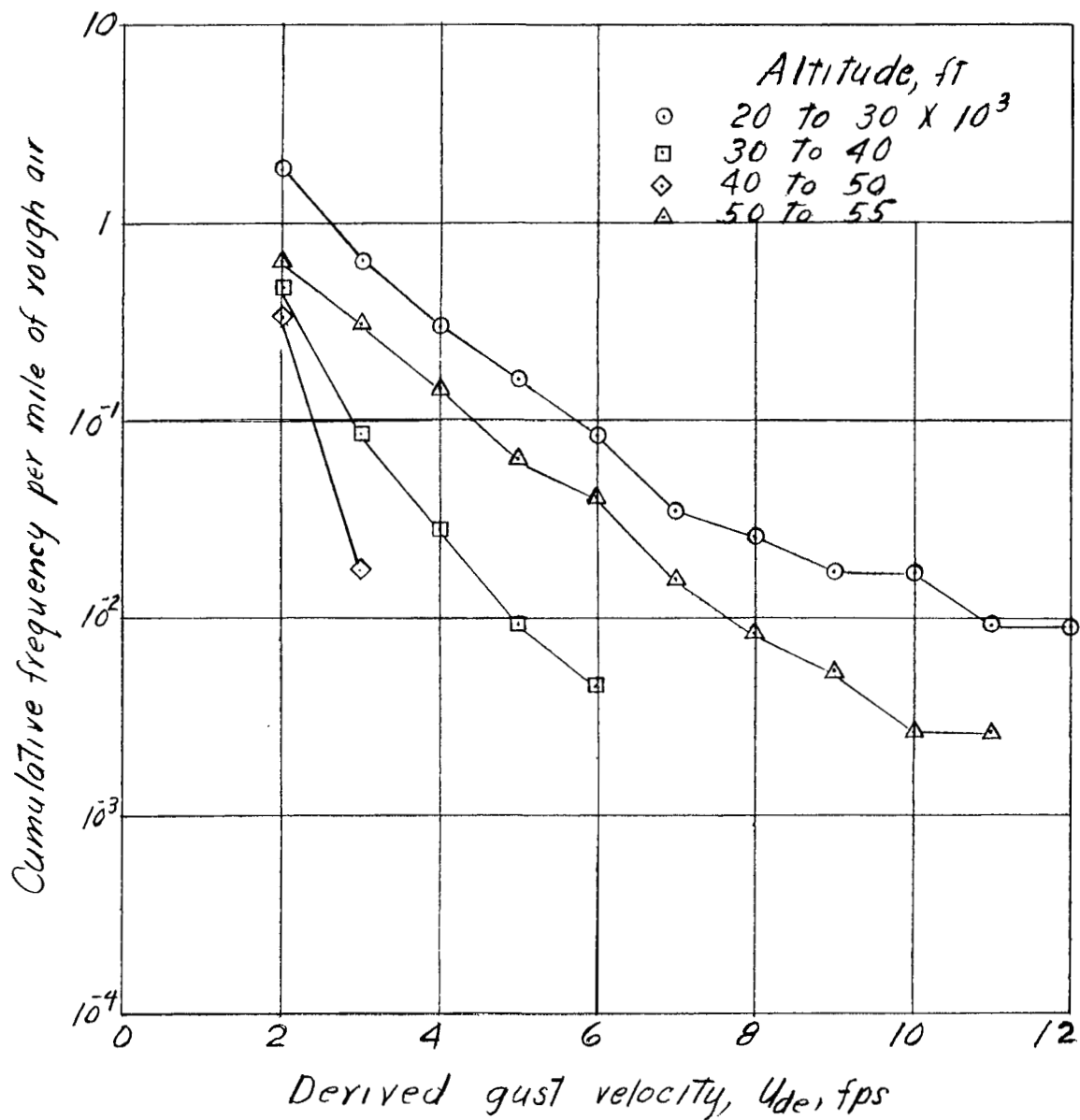
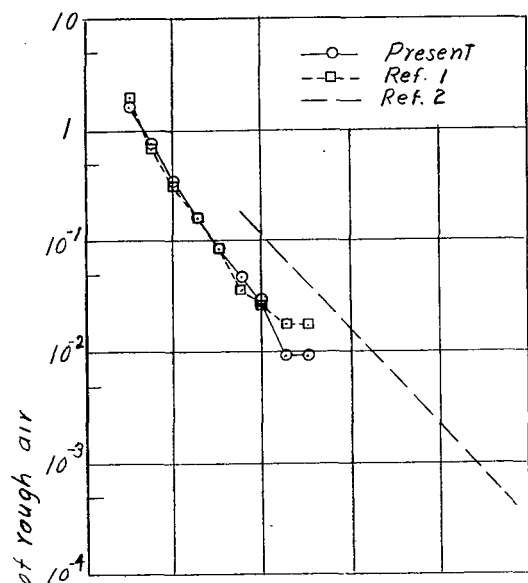
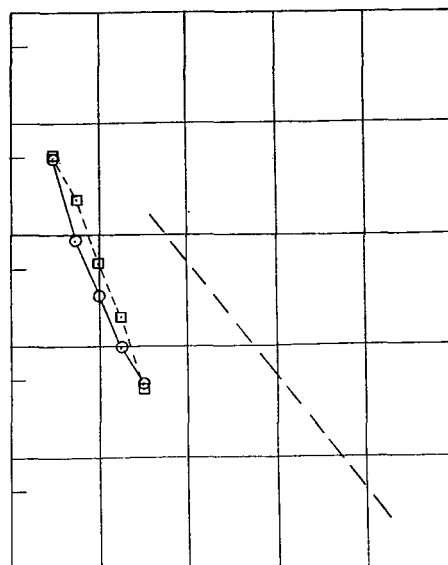


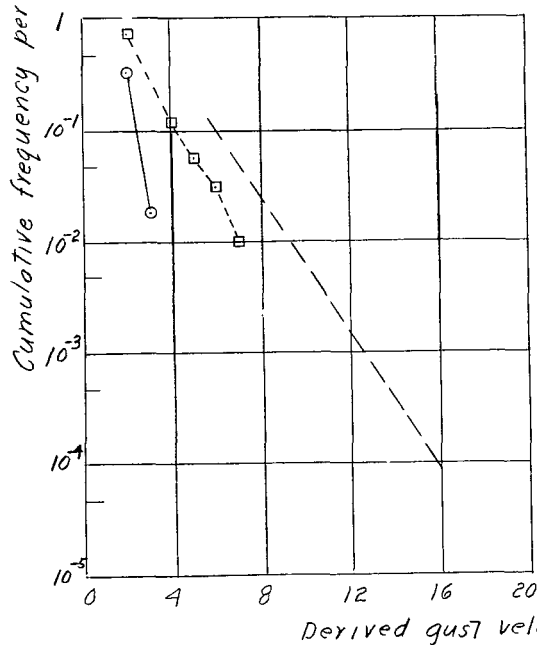
Figure 4.- Variation with altitude of the frequency of exceeding given values of gust velocity per mile of rough air.



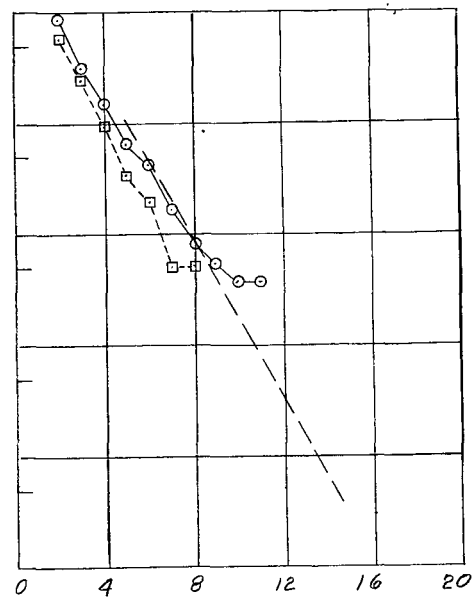
(a) 20,000 to 30,000 feet.



(b) 30,000 to 40,000 feet.



(c) 40,000 to 50,000 feet.



(d) 50,000 to 55,000 feet.

Figure 5.- Comparison at various altitudes of present results on the frequency of exceeding given values of gust velocity per mile of rough air with results from references 1 and 2.

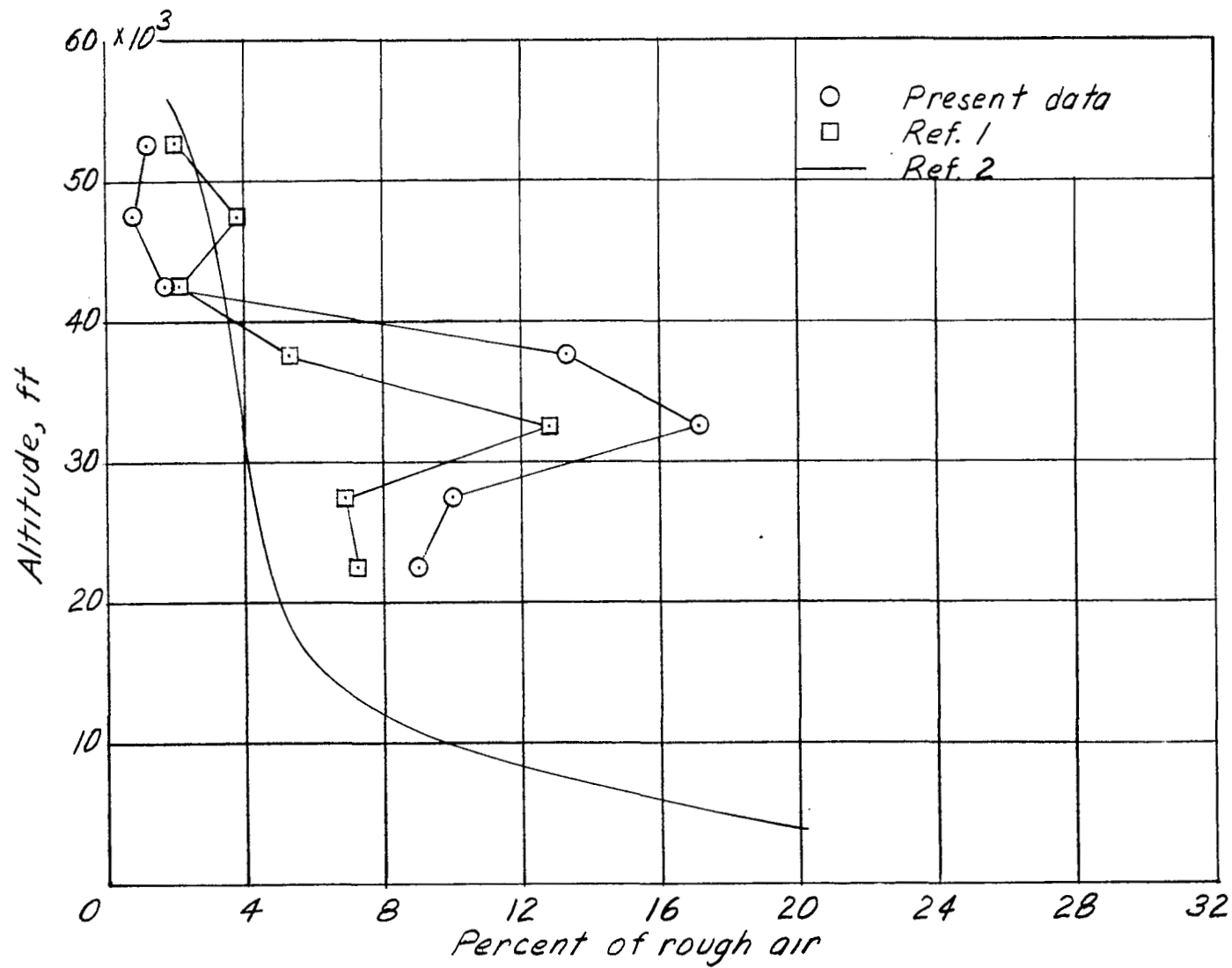


Figure 6.- Variation in percent of clear-air turbulence with altitude.

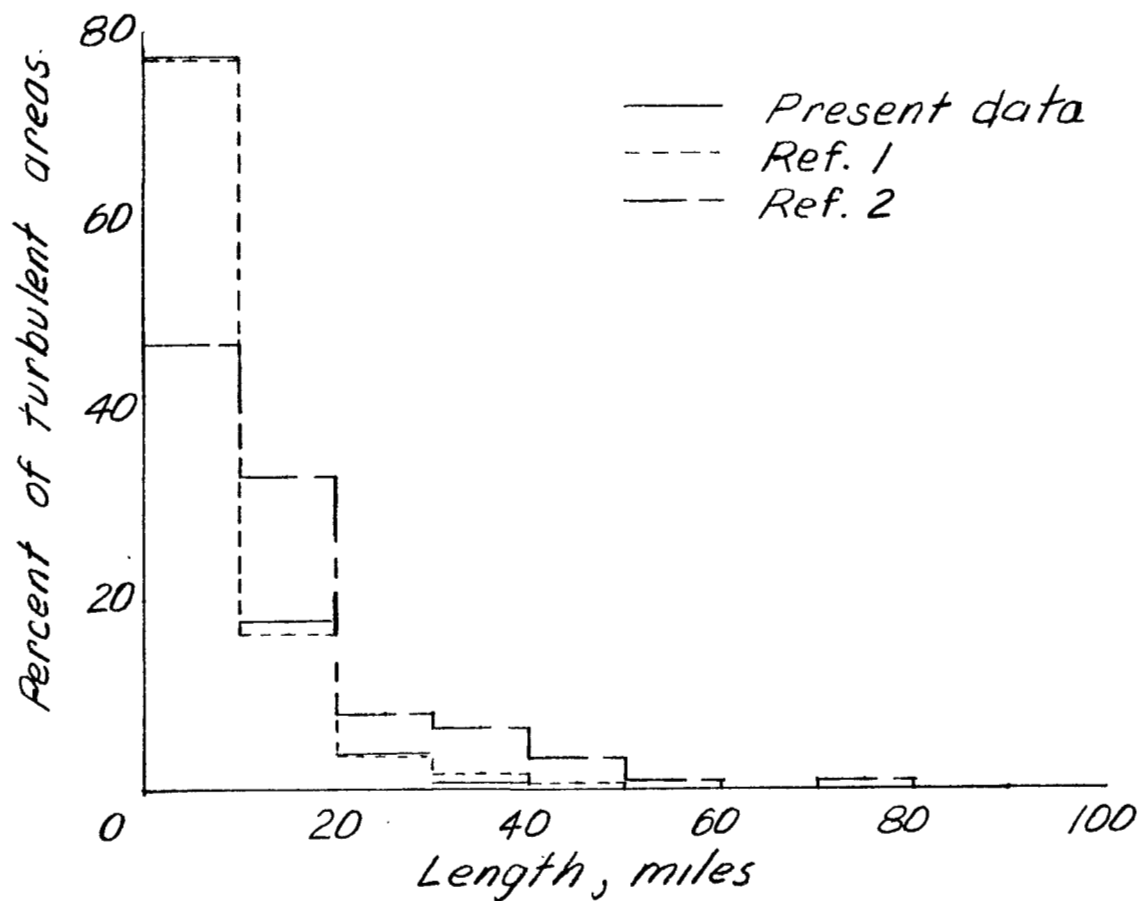


Figure 7.- Distribution of the lengths of turbulent areas for altitudes between 20,000 and 55,000 feet.